Utilizing Quantum Cascade Lasers for Gas Sensing in the Mid-Infrared

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ABSTRACT

Using Wavelength Electronics' precision temperature controller and low noise Quantum Cascade Laser (QCL) driver, researchers at Princeton University developed a sensor that was designed around a QCL to simultaneously measure nitrous oxide (N_2O) and carbon monoxide (CO). The sensor is compact and field-deployable, requiring much less power and having a much smaller footprint and mass than previous sensors, while increasing the accuracy of concentration measurements. The most accurate measurements were 0.15 parts-per-billion-by-volume (ppbv) for N_2O and 0.36 ppbv for CO. These accuracies well exceed the requirement of 1 ppbv to be considered "high stability" in the field of atmospheric sensing.

WHY?

Nitrous oxide (N_2O) is a greenhouse gas that poses a greater threat to global warming potential than carbon dioxide, and is currently increasing in the atmosphere. The understanding of what is driving this increase, and whether it is human-related is an important scientific question that remains unanswered.

Part of the reason that the question surrounding N_2O is still unanswered is that its emissions are poorly constrained in both space and time, making it difficult to measure. Another driving factor for confusion with respect to N_2O is that atmospheric levels fluctuate naturally, as nitrogen levels in the soil and bodies of water change.

Simultaneous detection of N_2O and CO concentrations allows identification of natural and fossil fuel combustion sources of N_2O.

Portability of the sensor is necessary for making field measurements. This allows data to be collected during natural or human-caused fluctuations, and to find correlations between outdoor weather and rises in N_2O concentrations.

PROBLEMS WITH OLD SENSORS

Systems that were designed prior to the advent of QCLs required bulky laser systems that had mid-infrared (mid-IR) emission wavelengths. These lasers generally also required large cooling mechanisms, which added to the footprint and the overall mass of the system.

Older systems also didn't have high enough accuracy for the required measurements.

Another shortfall that many of the previous systems had is that they were designed to be able to take measurements in a laboratory environment, and were not easily (if at all) transferrable to the field to take measurements.

Previous systems also commonly employed a closed-path setup, which is prone to sampling artifacts due to the tubes and vacuums that are required for closed-path sensing. Additionally, these closed-path geometries were ill-suited for handling high-frequency changes in the measurement, and would frequently broaden the data if a high frequency change were to occur.

HOW?

In order to take advantage of the isolated absorption bands of both N_2O and CO, a wavelength range in the mid-IR was chosen. This fit well with the utilization of a QCL for the optical sensor. The QCL chosen had a center wavelength of 4.5μm.

Real-time calibration (for changing conditions in the field), was made feasible by an in-line acetylene (C_2H_2) reference cell, which was placed after the output of the QCL. Acetylene has a well-known spectra in this wavelength range, and is not naturally abundant, allowing calibration of the sensor based on the known values that the acetylene cell should produce.

Utilizing LabVIEW™ software, wavelength modulation spectroscopy was used to simultaneously detect both the second and fourth harmonic absorption spectra of the three gases under consideration. The LabVIEW software was able to model and fit (at 10Hz) the concentrations of nitrous oxide, carbon monoxide, and acetylene.

To make the sensing system portable, an open-path multi-pass sensing system was chosen over a closed-path system. Closed path systems require large vacuums and other parts that make the system not easily portable. An open-path system allows the sensor to be field-deployable, and to take real-time measurements. In addition to the sensing system, the researchers used a weather station to monitor the temperature and humidity of the location where the measurements were taken. This allowed the researchers to see how water vapor influenced their measurements.

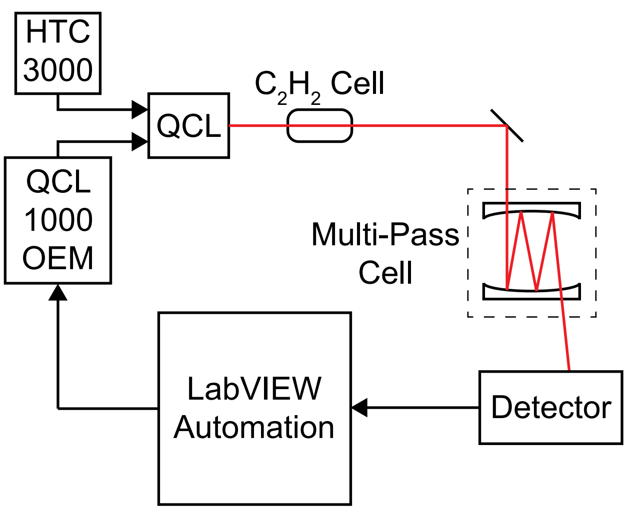

Figure 1. Utilizing the QCL1000 OEM and the HTC3000 to precisely drive the QCL and maintain its temperature, the researchers were able to create a high-accuracy, portable atmospheric gas sensing system as shown.

LabVIEW is a trademark of National Instruments.

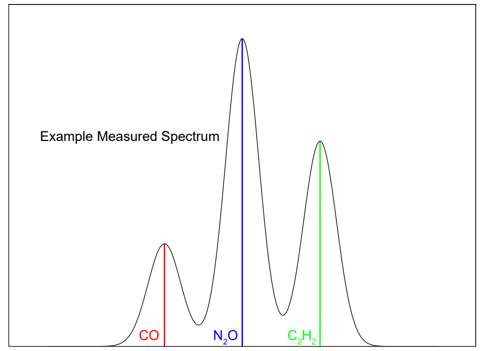

Figure 2. The region chosen had isolated absorption bands for carbon monoxide (CO), nitrous oxide (N_2O), and acetylene (C_2H_2). The overall spectra can be decomposed into the three original absorption bands due to the separation between them. ***Simulated data.

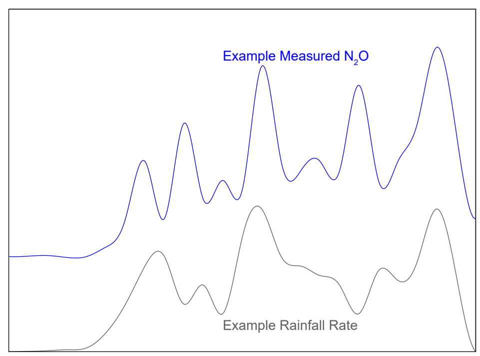

Figure 3. Rainfall during field-testing showed a corresponding increase in N_2O levels. ***Simulated data.

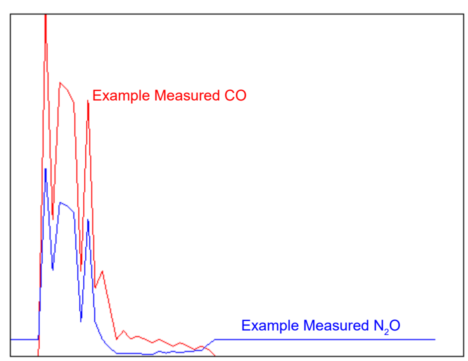

Figure 4. A strong linear correlation between N_20 and CO levels was found. ***Simulated data.

***For actual data, see *Tao et al*, **Reference 3**.

WAVELENGTH SOLUTIONS

The performance of the QCL-based sensor rests on the QCL itself. The QCL will not function optimally if it is not accurately temperature-controlled and driven with low-noise current. As such, both the temperature controller and QCL driver should be chosen to minimize noise and maximize stability.

The center wavelength of QCLs is inherently dependent on the operating temperature of the QCL. A varying temperature changes the energy gaps in the semiconductor layers of the QCL, and thus, changes the center wavelength. So, for a stable QCL, the operating temperature must be stable as well. For this application, the researchers required stable temperature at 40°C, and chose to use the HTC3000, which has stability as low as 0.0009°C.

QCLs require a specific driver that is designed for low-noise current supply to the laser. If there is noise in the current supply, that noise will be translated to instability in the output of the QCL, causing linewidth broadening. The low-noise laser driver that was chosen was the QCL1000 OEM. This driver is specifically engineered to have the lowest noise on the market, with RMS Noise Current of 0.7μA, and Average Noise Current Density of 2.0 nA/√Hz, giving the researchers the narrow linewidth required for this application.

Optimally controlling the temperature and providing low-noise current to the QCL enabled repeatable scans, which was crucial to the success of the project.

In addition to the stable temperature control and low-noise laser driver, the size and mass of the components chosen was important for this application. By choosing the HTC3000 and the QCL1000 OEM, the researchers were able to fit both the temperature controller and the laser driver into a single box, simplifying their setup and minimizing the footprint required for their detection system.

PRODUCTS USED
HTC3000
QCL1000 OEM

KEYWORDS
Quantum Cascade Laser, nitrous oxide, N_2O, carbon monoxide, CO, atmospheric sensing, temperature control, laser driver, low noise, thermoelectrically cooled, wavelength modulation spectroscopy, infrared, greenhouse gas detection, global warming

USEFUL LINKS

1. HTC3000 Product Page
2. QCL1000 OEM Product Page
3. Lei Tao, Kang Sun, M. Amir Khan, David J. Miller, and Mark A. Zondlo, "Compact and portable open-path sensor for simultaneous measurements of atmospheric N2O and CO using a quantum cascade laser," Opt. Express **20**, 28106-28118 (2012)

REVISION HISTORY

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REVISION	DATE	NOTES
A	April 2017	Initial Release